Temperature Control of Pulse Heated Specimens in a Kolsky Bar Apparatus Using Microsecond Time-Resolved Pyrometry¹

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Analysis of machining processes is important in the understanding and improving of manufacturing methods. The modeling of machining processes relies on high-strain-rate, high-temperature material properties. A Split-Hopkinson (or Kolsky) bar has been developed at NIST, for this purpose. By heating the material specimen rapidly with a controlled current pulse prior to the mechanical impact in the bar, structural changes in the specimen are inhibited, thus better simulating conditions during machining. A stress-strain relationship can be determined at various temperatures for a range of materials.

For the elevated temperature Kolsky experiments it is essential for the specimen to be maintained at a constant and uniform temperature prior to the dynamic loading. We describe the development and implementation of a near-infrared micro-pyrometer (NIMPY) to the precision control of Kolsky specimen temperature preceding the mechanical impact. The pulse-heating system can be operated either in the transient mode, where the current to the Kolsky specimen is switched off at a preset temperature or time, or in the brief steady-state mode, where the specimen is heated rapidly to achieve the desired temperature (in the range from 400 K to 1300 K) in a short time (about 200 ms) and then held isothermally for a brief period (<2 s). The sensing signal for the feedback is provided by the NIMPY. Based on a feedback control algorithm, a dedicated computer operates a solid-state switch, consisting of field-effect-transistors (FETs), with a fast response time (<5 ms), which controls the current to the Kolsky specimen to achieve isothermal condition.

A brief description of a model of the pulse heating process is provided and the predicted specimen temperature history is compared with measured temperature data.

¹ Paper presented at the Fifteenth Symposium on Thermophysical Properties, June 22 –27, 2003, Boulder, Colorado, U.S.A.

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1. INTRODUCTION

The prediction and measurement of rapidly changing temperatures near the cutting tool tip have been long-term goals for machining research. Modern analytical tools such as the finite element analysis (FEA) method are being used to model the machining processes in an attempt to provide a predictive capability for parameters such as cutting temperature and forces. However, efforts to use the FEA method to model machining processes have been hampered by the lack of adequate material properties for the high strain rates and rapid heating encountered in modern machining processes. During the cutting of metals, i.e. machining, rapid heating occurs (on the order of 5 x 10⁴ K s⁻¹) up to temperatures on the order of 1300 K, as well as very high strain rates (in the range of 10³ to 10⁶ s⁻¹ [1]). A new experimental apparatus at the National Institute of Standards and Technology (NIST) has been developed to produce high rate dynamic loading while simultaneously pulse heating the specimen with electric current.

Traditionally, the Kolsky bar test is done at room temperature, but to determine a stress-strain function useful for modeling machining processes, high temperature material properties are needed. Therefore, the NIST Kolsky bar apparatus has been integrated with an existing facility that provides a controlled high current pulse. Although methods have been developed for heating specimens prior to testing in a Kolsky bar [2], there is currently no method for preheating a specimen quickly enough in a Kolsky bar apparatus to simulate the conditions that occur during a high-speed machining operation.

The success of the elevated temperature Kolsky experiments is greatly dependent on the reliability and accuracy of the main components of the temperature control system, of which the pyrometer is an important one. A near-infrared micro-pyrometer (NIMPY) has been specifically built to suit this purpose. It consists of a refractive 5x objective lens with a numerical aperture of 0.14 attached to a traditional microscope body. Radiance is measured with an InGaAs detector with a time resolution of $1~\mu s$. The temperature range of interest for most materials is from 700~K to 1300~K. The pyrometer has been calibrated in this range and is shown to have a good signal-to-noise ratio. The pyrometer was originally set up as a measurement device with the Kolsky bar apparatus but is currently being used as both a measurement and a control instrument to monitor and control specimen temperature.

The temperature control system, consisting principally of the NIMPY, the Field Effect Transistors (FETs), and a temperature control algorithm, can be run in various modes depending on the type of control desired. The simplest of these modes is the 'Time-Control Mode' where the current is passed through the specimen for a preset time after which it is switched off. In the 'Time + Temperature Control Mode' both a time and a temperature value are preset in the computer program. When the desired temperature is reached the current to the specimen is switched off, unless the system is timed out earlier. A more advanced mode of operation for temperature control is the 'Isothermal Control Mode', where the plateau temperature and time are preset. The process is based on rapid resistive heating of the specimen up to the preset temperature in a short time (~500 ms) and maintaining the specimen at this temperature under steady-state conditions for a brief

period (50 ms to 2000 ms) before switching off the current to the specimen. The operational characteristics of the control system are described in more detail in the subsequent sections.

2. MEASUREMENT AND CONTROL METHOD

The 'Time + Temperature Control Mode' is a transient technique where the amplified temperature signal from the pyrometer is acquired by the control computer and processed by the control algorithm with a cycle time of 0.7 ms. When the desired temperature is reached the current is switched off automatically. While this mode is suitable for some applications, elevated temperature Kolsky tests done in this mode have the disadvantage that the mechanical impact has to take place when the temperature is rapidly increasing or decreasing, so, its difficult to get good repeatability for the impact temperature.

The 'Isothermal Control Mode' combines the transient and the brief steady-state techniques. The specimen is maintained at a more-or-less constant temperature with the feedback control system which controls the current through the specimen. The computer-controled feedback system operates a solid-state switch composed of the FETs. The sensing signal for the FETs is provided by NIMPY. Such solid-state switches are ideal for switching high currents on and off in millisecond-resolution pulse heating tests, as developed and described by Matsumoto and Ono [3]. More applications of solid-state switches for pulse heating applications have been discussed by Matsumoto and Cezairliyan [4] and Matsumoto, Cezairliyan, and Basak [5].

Figure 1 is a schematic diagram showing the temperature vs. time trace for a Kolsky specimen controlled with the feedback control technique. The specimen undergoes initial rapid heating from room temperature, T_0 , to a preset high temperature, T_i , in period A, followed by a brief steady-state period B, and a final cool-down period C. When the temperature of the specimen reaches the preset plateau temperature, the PID control algorithm takes over and adjusts the current instantaneously with a high time resolution in an effort to balance the imparted electrical power to the specimen with the total power loss from the specimen, resulting in the temperature arrest. The duration of periods A and B are varied depending on the requirements of the experiment. Period A can be varied by changing the imparted power to the specimen and the electrical resistance of the pulse-heating circuit, while period B can be varied by entering its value in the feedback control program.

3. MEASUREMENT AND CONTROL SYSTEM

A schematic diagram of the measurement and control system for the Kolsky bar apparatus is shown in Figure 2. The electrical pulse heating circuit consists of the Kolsky specimen sandwiched between two bars, in series with a battery bank, a standard resistor, a variable resistor, and a computer controlled high speed FET switch. Details of the pulse heating system are discussed in more detail by Basak, et al. [6]. A constant flow of argon is maintained to form an inert atmosphere around the specimen. The main elements of the

feedback control system are the pyrometer (NIMPY), the FET switch, and the control algorithm. These elements are described below in more detail.

A typical elevated temperature Kolsky experiment is initiated by sending simultaneous trigger pulses to multiple devices (see Fig. 2). The mechanical relay switch is first closed. The control voltage is then sent to the gate of the FETs, which allows for the flow of a controlled current through the specimen. This results in the rapid temperature rise, followed by a temperature arrest. At the same time, a trigger is sent to the 'Delay Generator and Driver Unit', where a preset delay is entered. This delay (150 ms to 350 ms) is comparable to the time it takes for the specimen to heat from room temperature and stabilize at the desired high temperature, minus the time required by the mechanical system to fire the projectile. This timing arrangement ensures that the mechanical impact to the specimen occurs after the specimen has reached a steady-state condition. Trigger pulses are also sent simultaneously to all the recording instruments, which acquire the data with a high resolution.

3.1 Pyrometer

The high-speed near-infrared micro-pyrometer (NIMPY) was designed using a commercial 5x objective lens (NA 0.14) with a 50 % transmission beam-splitter to view the specimen. Figure 3 shows a schematic of the NIMPY. The voltage signal from this pyrometer is used for both temperature measurement and control. The specimen is located visually and then realigned to maximize the infra-red signal. The detector is a temperature stabilized (– 25 °C) InGaAs photodiode whose spectral responsivity peaks at 1.5 μ m. The photodiode is used without any spectral filtering. Regular glass optics are used, since glass transmits to 1.7 μ m. The preamplifier used for the measurements has a minimum bandwidth of 800 kHz for all the gain ranges and was set to operate at 1 μ s resolution.

The pyrometer was calibrated using a blackbody operating at known temperatures and emissivity (0.99 \pm 0.005). The reflectance of the 316 stainless steel was measured in the near-infrared wavelength region along with the spectral power responsivity of the InGaAs detector. The spectral reflectance was weighted by the spectral power responsivity to obtain a single band-weighted reflectance value of 0.52, and the emissivity was determined using 1-r. The thermodynamic temperature was determined using the radiance temperatures obtained from the pyrometer calibration function and the corresponding emissivities.

3.2 Switch

The solid-state switching system consists of 20 FETs connected in parallel with a total of 80 protective resistors, 0.1 Ω each. The specifications of the FETs are given in Table I. The switch is controlled by a control voltage (gate-source voltage) which is in the range from 0 V to 10 V. In principle, current through an individual FET may be approximated by a quadratic function of the control voltage,

$$I_{sw} = K_c (V_c - V_t)^2 \qquad (V_c \exists V_t)$$
 (1)

where I_{sw} is the current through the switch, K_c is the gain of the current, V_c is the control voltage, and V_t is the threshold voltage. The switch also contains a control unit, which transfers the control voltage from the control computer to the FETs. The control unit is essentially a differential amplifier of unity gain, consisting of two operational amplifiers.

In the feedback switching mode, high current passes through the FETs, which are being controlled continuously in accordance to Eq. 1. The resulting heat dissipation in the units are much larger than that in the simpler on-and-off switching mode. This heat dissipation limits the maximum current capacity of the switching system. The heat generation in the FETs is monitored and calculated in real time, and the resultant temperature rise is estimated. When run in the 'Protected Mode', the control program will switch off the current automatically when the FET temperature exceeds 380 K. The 'Protected Mode', however, slows down the mean loop duration for temperature control.

3.3 Feedback Control Algorithm

The proportional, integral, and differential (PID) feedback control technique is widely used in laboratory and industrial applications. The details of this theory can be found elsewhere [4, 7]. The feedback temperature control was performed using a dedicated personal computer with analog-to-digital (A/D) and digital-to-analog (D/A) converters with 12-bit resolution. The steps involved in a single loop of control include the following:

- i) Output voltage from the pyrometer (NIMPY) is sampled by the A/D converter.
- ii) A radiance temperature is calculated from the output voltage.
- iii) A corresponding control voltage is computed using the algorithm.
- iv) The digital value of the control voltage is converted to real voltage by the D/A converter.
- v) The control voltage is transferred to the gate of the switch through the differential amplifier.
- vi) The current flowing through the FETs is altered according to Eq. 1.

The stability and convergence of the control system are strongly dependent on the values of K_p , K_i , and K_d , which are the proportional, integral, and differential constants, respectively. Numerous tests were conducted by varying the values of these constants to best optimize the system for a given set of conditions. These constants are especially sensitive to the specimen resistance, contact resistance between the specimen and bars, desired specimen temperature, ambient temperature, and argon flow rate.

Tests were also conducted with a simplified proportional and differential (PD) control method. This method ignores the integral component of the equation while computing the

control output by assuming the value of the integral constant to be infinity ($K_i = 4$). The advantages of the PD control mode include the simplicity of calculation, resulting in smaller loop time and lesser sensitivity to varied operational conditions. It does have the disadvantage that the temperature offset from the set-point is usually larger. All results presented in the next section are based on the PD control mode.

4. RESULTS

Temperature signals from the specimen were measured and recorded for each test. A single-channel spot pyrometer (NIMPY) was used for the measurement of temperature, whereas an imaging pyrometer was used to map the temperature distribution of the specimen during heating. Tests were performed on cylindrical specimens of 316 stainless steel with the following dimensions: 4 mm diameter and 2 mm length. The specimen was held between the bars by friction only. This is necessary to enable free expansion of the specimen during impact. A flexible foil of graphite (Grafoil®) was attached to each of the bars to enable better electrical contact between the specimen and the bars. The use of the grafoil eliminated hot spots on the specimen, resulted in better uniformity in specimen temperature, and eliminated sparks during heating.

Figure 4 shows a temperature vs. time trace of a test conducted in 'Time + Temperature Control Mode'. This is a transient test where the current is switched off when the specimen temperature reaches the preset temperature (unless the system is timed out). For this test, the preset specimen temperature was 1060 K and the actual maximum temperature was 1065 K. The 5 K overshoot was largely due to the fact that the grafoil, which heats significantly during the test, continues to conduct the heat to the specimen for a few milliseconds after the current is switched off.

Figure 5 shows test results for three tests conducted in the "Isothermal Control Mode'. The average plateau temperatures obtained for these tests are 870 K, 980 K, and 1095 K. Figure 6 (a), (b) and (c) shows the individual plots with the plateau region magnified. The details of the tests are given in Table II. Set point temperature (Column 1) is the desired plateau temperature of the specimen, preset through the control software before the start of the test. Average plateau temperature (Column 2) is the average of the actual specimen temperature at the plateau after it has reached stability. ΔT (Column 3) is the difference between the set-point temperature and the average plateau temperature. Column 4 is the standard deviation from the mean plateau temperature. Time to plateau (Column 5) is the time required for the specimen to reach the preset plateau temperature since applying power to the specimen. Time to stability (Column 6) has been arbitrarily defined as the time required for the temperature to fluctuate less than ±2 K from the average plateau temperature since the start of the plateau.

5. MODELING PULSE HEATING OF THE SPECIMEN

We have developed a one-dimensional model of the pulse heating experiment, based on the heat equation with temperature-dependent coefficients, that predicts a specimen temperature history that is consistent with the test results. The high DC current I in the circuit causes rapid Joule heating to occur almost entirely in the specimen, which has a much larger electrical resistance because of its smaller diameter compared to that of the bar. Losses due to convection and radiation are insignificant compared to this heating per unit volume $V_{\mathcal{S}}$ of the specimen,

$$\dot{q}(t) = I^{2}(t)R_{s}(t)/V_{s} = I(t)E_{s}(t)/V_{s}$$
(2)

where R_s and E_s are the resistance and potential difference across the specimen, respectively. This source term is large because the maximum current in the circuit is order of magnitude 1000 A, the maximum voltage across the specimen is about 2.5 V, and the specimen volume is small, $2.5 \cdot 10^{-8} \, m^3$. Furthermore, since the volume of the bar is on the order of 10^3 times greater than that of the specimen, most of the bar remains at its initial temperature during the several hundred millisecond time interval of the test.

We assume that the main system parameter affecting heat transfer to the bar is an interface thermal contact conductance H_C , resulting from imperfect contact between the specimen and bar over the specimen cross-sectional area A_S . Assuming that the contact pressure is on the order of $100 \, kN/m^2$, then at room temperature, $\theta_0 \approx 300 K$, the approximate range for the contact conductance for steel is $300-11000 \, W/(m^2 K)$ [8]. H_C increases with interface temperature, pressure, and smoothness of the two contact surfaces. Unfortunately, there is not much data available on these variations. Therefore, our approach is to treat H_C as a constant parameter, and numerically determine the value for which the model best fits the measured temperature data. The best fit was found for $H_C \approx 4500 \, W/(m^2 K)$, as shown in Figure 7. This result is consistent with the available data (Ref. 8). For comparison, the specimen-center temperature is also shown for the adiabatic case $H_C = 0$ (no heat loss to the bar), and for the case $H_C = \infty$ (bar is an isothermal heat sink at the ambient temperature θ_0).

6. DISCUSSION AND CONCLUSION

In general, the test results under discussion show a rather high degree of temperature control (a maximum standard deviation of about 1 K). The magnitude of ΔT increases slightly with the increase in plateau temperature, the maximum deviation from set-point being limited to 1.5 K. The standard deviation decreases with increase in plateau temperature, due to the better signal-to-noise ratio obtained at higher temperatures. The

level of control attained is adequate for the current application. However, by tuning the system better, it is possible to obtain shorter time to temperature stability and to reduce the initial oscillations in temperature. Work is currently in progress to obtain a more optimized system to provide a higher degree of repeatability to the elevated temperature Kolsky experiments.

The calculated result from a one-dimensional model of the pulse heating experiment was found to be consistent with available data. The bounds for the predicted temperature were also generated for the isothermal and the adiabatic case, which were found to be reasonable.

7. ACKNOWLEDGEMENTS

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Table I. Specifications for Individual FETs and the Overall Switch Used in the Temperature Control of Kolsky Specimens

Experimental Parameters	FET	Switch	
Maximum continuous current	145 A	2900 A	
Maximum heat dissipation	500 W	10 kW	
Maximum response time	340 ns	340 ns	
Control Voltage (V _c)	0 - 20 V	0 - 20 V	
Threshold Voltage (V _t)	3.6 V	3.6 V	
Resistance	$11~\mathrm{m}\Omega$	$1.8~\mathrm{m}\Omega$	
Gain (K _c)	27 A·V ⁻²	530 A·V ⁻²	

 Table II. Details of Isothermal Tests Performed on Kolsky Specimens.

Temper	rature (K)	ΔT (K)	Std. dev. (K)	Time to plateau (ms)	Time to stability (ms)
Set point	Plateau avg.				
					_
869	869.2	0.2	1.1	450	125
982	980.8	-1.2	0.8	525	100
1096	1094.5	-1.5	0.3	670	70

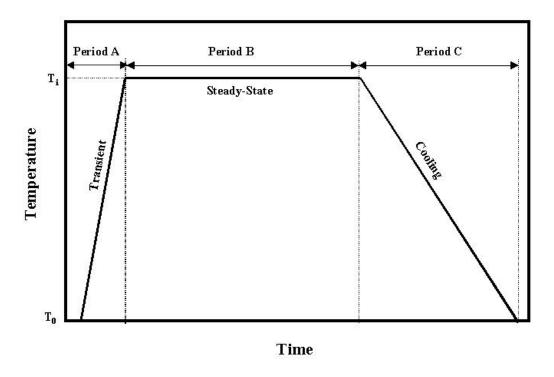


Fig. 1. Schematic diagram showing the temperature vs. time function for a typical isothermal test.

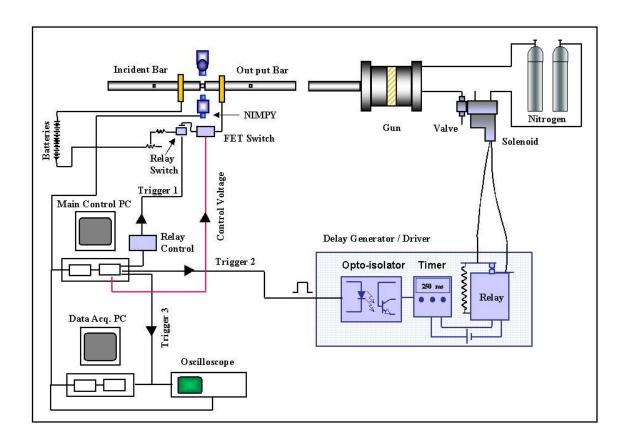


Fig. 2. Schematic diagram of the measurement and control system for the Kolsky bar apparatus.

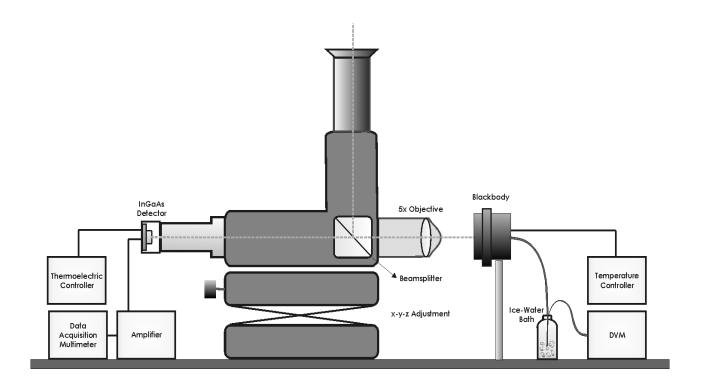


Fig. 3. Schematic of the near-infrared micro-pyrometer (NIMPY) along with calibration instrumentation.

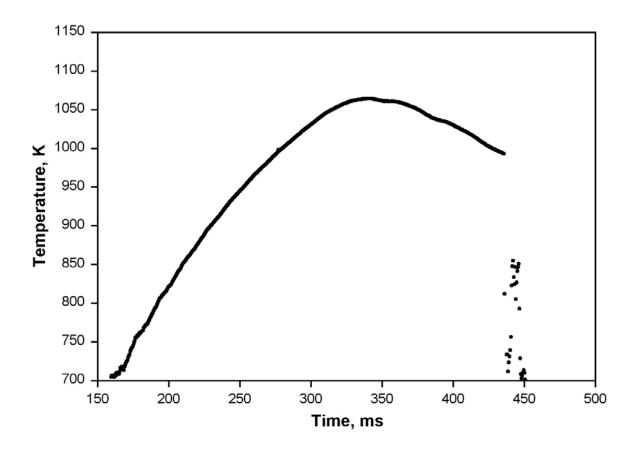


Fig. 4. Results of a temperature control test conducted in the transient (Time + Temperature Control) mode.

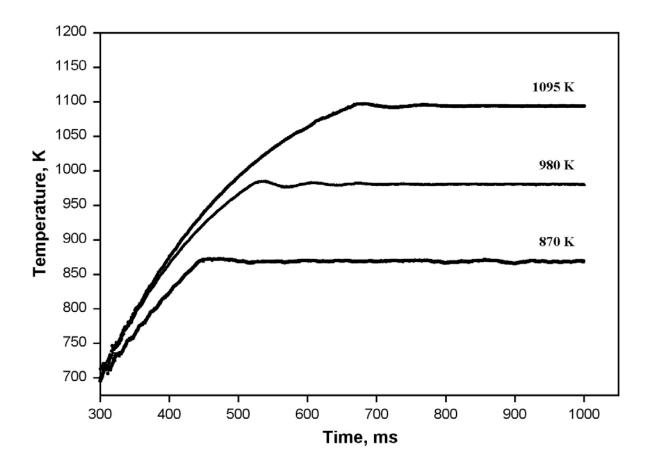


Fig. 5. Results of temperature control tests conducted at three temperature levels, in the transient plus brief steady-state (Isothermal Control) mode.

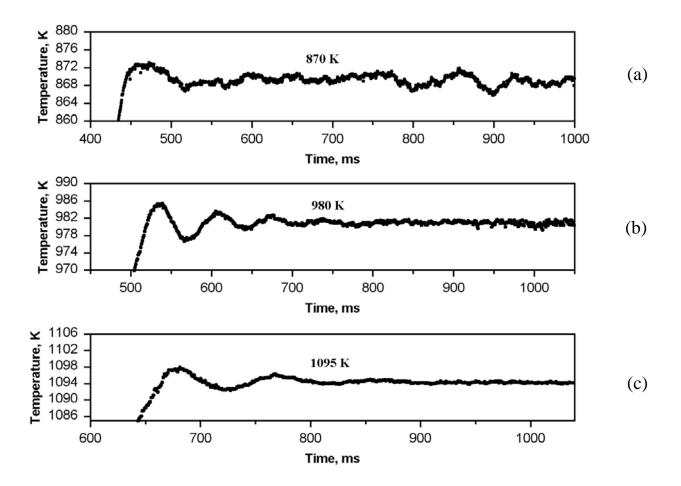


Fig. 6. Results of the temperature control tests shown in Fig. 5, with the plateau region magnified. The average plateau temperature is (a) 870 K, (b) 980 K, and (c) 1095 K.

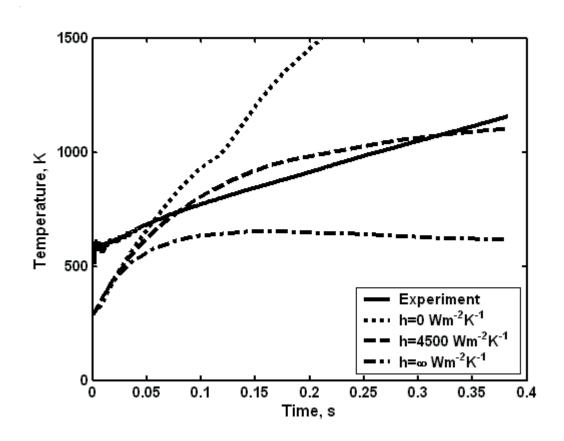


Fig. 7. Temperature history of the specimen as predicted by the model along with measured temperature data.